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DEVELOPMENT AND EVALUATION OF BRAZE ALLOYS FOR VACUUM FURNACE BRAZING

by K. L. Gustafson

Prepared by
AEROJET-GENERAL CORPORATION
Sacramento, Calif.
for Lewis Research Center

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FOREWORD

The research described herein, which was conducted by Aerojet-General Corporation, Liquid Rocket Operations, was performed under NASA Contract NAS 3-2555 with Mr. J. M. Kazaroff, Chemical Rocket Division, NASA Lewis Research Center, as Technical Manager. The report was originally issued as Aerojet-General Report No. 8800-26, November 1965.

ABSTRACT

A report of the results of an investigation of 11 braze alloy systems, 8 of which were developed by the Aerojet-General Corporation, as alternatives for the copper-gold commercial alloy (Nicoro) widely used to vacuum braze large rocket engine tubular thrust chambers.

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I. SUMMARY

A program was conducted to develop an alternative braze alloy for the copper-gold commercial alloy (Nicoro) widely used to vacuum braze large rocket engine tubular thrust chambers. The use of this alloy on extremely large thrust chambers, such as the M-1 engine, would result in inordinate costs. Copper and 10 copper-base alloys were investigated; eight of these copper-base alloys were non-commercial alloys developed under this contract. Two of these alloys, AGC-200 and AGC-201, proved to be equal in all respects to the commercial alloy Nicoro. The remaining six of these new alloys contained small additions of silicon and were somewhat weaker than Nicoro because of the formation of brittle silicide phases. Two commercial copper-base alloys, Anaconda 656 and Anaconda 651, compared favorably with Nicoro; however, additional research is required to reduce their impurity content for satisfactory high temperature vacuum brazing operations. Use of AGC-200 or AGC-201 braze alloy in preference to Nicoro will reduce the gold content by 57% and offer a 50% reduction in braze material costs.

II. INTRODUCTION

In 1956, the Aerojet-General Corporation Sacramento Plant developed the processing techniques for fabricating large size liquid rocket tubular thrust chambers by the high temperature furnace brazing process. This method of processing was successfully used in fabricating several thousand first-stage and second-stage thrust chambers for the Titan I, Titan II, and Gemini engine systems. It has since been adopted by the Aerospace industry as the most reliable and economical way for fabricating large tubular components requiring a very high linear footage of quality braze joints.

The selection of dry hydrogen as the furnace atmosphere for joining the above components permitted the Aerojet-General Corporation Materials Engineering organization to develop techniques utilizing relatively low cost braze alloys (i.e., approximately \$8.00 per lb). The decision to use a vacuum environment for furnace brazing of the M-1 Combustion Chamber at an optimum brazing temperature required the consideration of braze alloys with high purity containing elements with low vapor pressure. Because commercially available alloys of this category contain a high percentage of noble metals and cost approximately \$200.00 per lb, a program was initiated to develop and evaluate alternative lower cost braze alloys for use in joining of the M-1 components.

Various criteria in addition to those inherent with vacuum brazing guided the analysis and selection of alternative alloy compositions. The service environment required an alloy with high strength and toughness at cryogenic temperatures. Fit-up problems, inherent in the assembly of such a large tubular bundle, dictated the use of an alloy which is relatively insensitive to joint clearance variations.

The use of Alloy 718 in the assembly imposed a maximum braze temperature limitation of 1975°F; the maximum solution heat treat temperature.

A literature search was made to review and analyze commercially-available alloys (see Table 1) that could satisfy the aforementioned requirements. Nickel, gold, copper, and silver braze alloys were considered. Nickel-base alloys were discounted because of their inherent brittleness resulting from intermetallic compounds. Silver-base alloys were inadequate because of their relatively low strength. Hence, the gold-base and copper-base systems received critical study. This study resulted in the development of eight copper-base brazing alloys.

III. TECHNICAL DISCUSSION

A. BRAZE FILLER METAL REQUIREMENTS

1. Good strength and ductility in the room temperature to cryogenic (-423°F) temperature range. Crystal structure of the elemental constituents should be face-centered-cubic.

2. Elemental constituents should have relatively high vaporization temperature because vacuum brazing in the range of 0.5 to 5.0 microns is anticipated.

3. Minimum erosion and diffusion characteristics when used on AISI 347 stainless steel and brazed at approximately 75-degrees above the rated liquidus.

4. Melting point and brazing temperature in the range of 1700°F to 1975°F to minimize fixturing problems and to be compatible with heat treating requirements.

5. Insensitive to joint clearance variations as compared with copper.

6. Step-brazing capability (i.e., a sufficiently high brazing temperature to permit a second braze cycle, if required, at a slightly lower temperature).

7. Available in the three basic forms of wire, foil, and powder.

B. COPPER-BASE BRAZE ALLOYS

Copper was selected as the base material because of its desirable mechanical and physical properties as well as its low cost. The face-centered-cubic crystal structure of copper provides good cryogenic mechanical properties. Copper has approximately a 50% increase in tensile strength from room temperature to -423°F. It has a low critical vapor pressure which is essential for vacuum brazing (1.0 micron at 2085°F), alloy readily with the selected elements and forms a solid-solution alloy with nickel, cobalt, palladium, gold, and silicon. Copper has a relatively low melting point (1981°F) and requires minimum percentages of depressant elements to lower the melting point of the alloy to a point where brazing can be accomplished at

COMMERCIAL ALLOY SYSTEMS

Braze Alloy	Composition, %	Brazing Temperature, °F	Pressure, Microns
Nicoro	Cu 62 Au 35 Ni 3	1925	1-5
Nioro	Au 82 Ni 18	1800	1-5
Gemco	Cu 87.75 Ge 12.0 Ni 0.25	1800	1-5
Nicoro 80	Au 81.5 Cu 16.5 Ni 2.0	1750	1-5
1600N	Cu 52.5 Ni 9.0 Mn 38.5	1700	13-15
1700N	Cu 67.5 Ni 9.0 Mn 23.5	1800	15-20
1700CN	Cu 63 Ni 5 Cr 10 Mn 22	1850	20-25
Cusil	Ag 72 Cu 28	1500	1-5
Nicusil 3	Ag 71.15 Cu 28.10 Ni 0.75	1500	1-5

1975°F or below. The alloying elements selected and the percentage of the alloy constituents formulated were made upon the basis of each element forming a solid-solution alloy which would enhance the properties of the copper-base metal while meeting all of the specified basic requirements.

Generally, all constituents should have the same crystal form and have near-identical atomic diameters to produce a solid-solution alloy system. Variations in atomic diameters should not exceed approximately 14% from the base metal; however, limited solid-solubility can be achieved with some elements in small percentages. Some of the significant properties are shown in Table 2.

In this development program, two elements (cobalt and silicon) were added as alloying constituents. Although neither has the same crystal form as copper, they will go into solution with a copper-base alloy in a limited quantity.

Eight alloy compositions were developed and were assigned the designations: AGC-200, AGC-201, AGC-202A, AGC-202B, AGC-204A, AGC-204B, AGC-206A, and AGC-206B. All eight alloys are copper-base quaternary systems. The actual compositions (see Table 3) were arrived at by mathematical calculations (weight ratios) of published binary alloy systems. To prevent exceeding the maximum brazing temperature of 1975°F, a liquidus temperature maximum was established at approximately 1950°F. Sufficient gold is alloyed in AGC-200 and AGC-201 to depress the liquidus temperature of these alloys to 1925°F and 1950°F, respectively. Variations in the gold content were found to affect the melting point by the factor of approximately 4°F per each one percent of gold added. It was determined that the addition of 15% gold provided the capability for achieving some economic benefit (a reduction of gold by a factor of 57% from the prime commercial candidate Nicoro).

In addition, two commercial copper-base alloys, Anaconda 651 and Anaconda 656, were evaluated as potential braze alloys. The purity of these alloys was not to the level generally required for alloys intended as braze filler materials. The composition and properties of these alloys are shown in Table 4 together with the reference Nicoro alloy and OFHC copper.

C. SPECIMEN DESIGN AND PREPARATION

Two basic types of specimens were prepared to obtain both ultimate tensile strength and ultimate shear strength values for the alloy systems under study. The tensile specimens were prepared by machining AISI 347 stainless steel blocks as shown on Figure 1. The lap shear specimens were prepared in accordance with A.W.S. C3.1-63, "Standard Test for Brazed Joints" (see Figure 1). Three specimens of each type were vacuum furnace brazed with each of the test alloys. The use of both lap shear and tensile specimens was necessary to evaluate the newly-developed alloys as well as the commercial alloys.

PHYSICAL PROPERTIES OF ALLOYING ELEMENTS

Element	Atomic Diameter Angstrom Units	Crystal Structure	Melting Point ^{o}F	Vapor Pressure (Critical)
Gold	2.80	Face-Centered Cubic	1945.4	1 micron @ $2400^{o}F$ 0.1 micron @ $2175^{o}F$
Palladium	2.74	Face-Centered Cubic	2826	1 micron @ $2560^{o}F$ 0.1 micron @ $2320^{o}F$
Copper	2.54	Face-Centered Cubic	1981	1 micron @ $2085^{o}F$ 0.1 micron @ $1895^{o}F$
Cobalt	2.52	*Close-Packed Hexagonal	2723	1 micron @ $2720^{o}F$ 0.1 micron @ $2485^{o}F$
Nickel	2.48	Face-Centered Cubic	2647	1 micron @ $2500^{o}F$ 0.1 micron @ $2295^{o}F$
Silicon	2.36	*Diamond Cubic	2570	1 micron @ $2235^{o}F$ 0.1 micron @ $2040^{o}F$

* Ordinary form, other forms known or probable.

Source: Handbook of Chemistry and Physics, Chemical Rubber Publishing Company
Metals Handbook, American Society for Metals
Vapor Pressure Data, Radio Corporation of America, Sarnoff Research Center

Table 2

AEROJET-GENERAL CORPORATION DEVELOPED ALLOYS

AGC	200	201	202A	202B	204A	204B	206A	206B
Composition, %	Cu bal Ni 3.0 Pd 4.5 Au 15.0	Cu bal Co 5.0 Pd 5.0 Au 15.0	Cu bal Si 3.5-4.0 Ni 0.5-1.5 Pd 0.5-1.0	Cu bal Si 1.5-2.0 Pd 0.5-1.5 Ni 0.5-1.0	Cu bal Si 3.5-4.0 Pd 5.0-6.0 Ni 3.3-4.0	Cu bal Si 1.5-2.0 Pd 5.0-6.0 Ni 3.3-4.0	Cu bal Si 3.5-4.0 Pd 9.0-10.0 Ni 6.0-6.75	Cu bal Si 1.5-2.0 Pd 9.0-10.0 Ni 6.0-6.75
Liquidus, ^{o}F	1925	1930	1875	1910	1825	1925	1830	1930
Brazing Temp., ^{o}F	1965	1970	1900	1950	1900	1975	1900	1975
Diffusion, in.	0.001	0.001	0.003	0.002	0.003	0.002	0.003	0.002
Erosion (At brazing temp.)	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Hardness (Brazement R_B)	58	60	60	94	84	80	89	88
Wet and Flow Characteristics	Very Good	Very Good	Very Good	Good	Very Good	Good	Very Good	Very Good
Peel Test Failure	Base Metal	Base Metal	Base Metal	Base Metal	Braze Joint	Base Metal	Braze Joint	Base Metal

Table 3

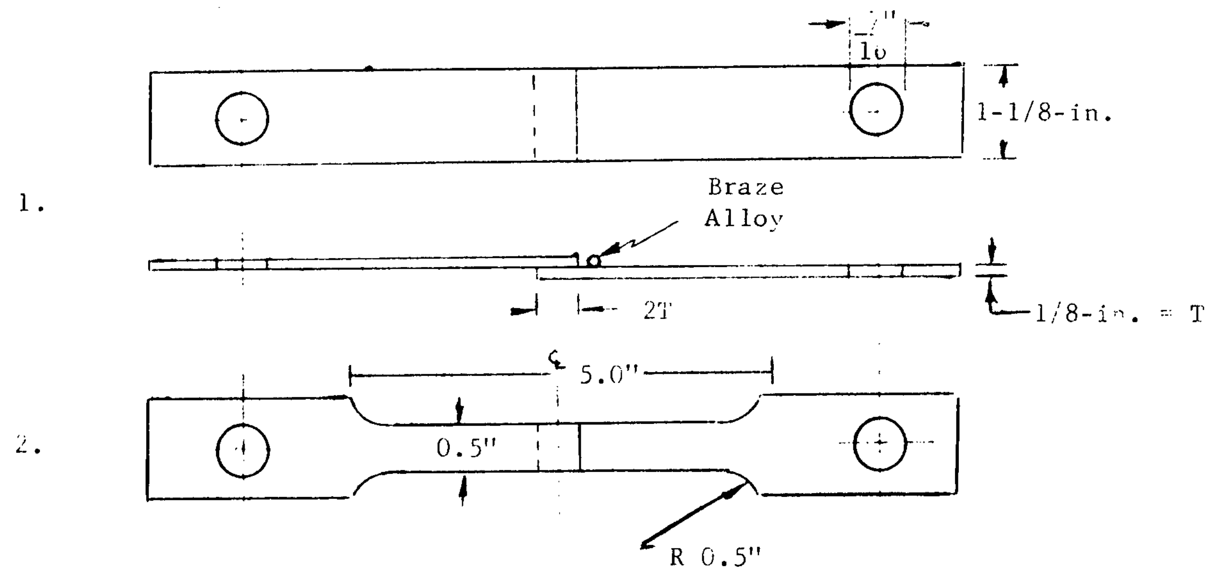
COMMERCIAL ALLOYS

Condition*	O.F.H.C. Copper	Nicoro (Wesgo)	Anaconda 656 (1010)	Anaconda 651 (1015)
Composition, %	Cu 99.9	Au 35.0 Cu 62.0 Ni 3.0	Cu 95.8 Si 3.10 Mn 1.10	Cu 98.25 Si 1.5 Mn 0.25
Liquidus, ^{o}F	1981	1886	1865	1931
Brazing Temp., ^{o}F	2030	1925	1900	1960
Diffusion, in.	0.001	0.002	0.003	0.003
Erosion	Nil	Nil	Nil	Nil
Hardness	40 R_F	75 R_B	65 R_B	52 RB
Wet and Flow	Fair to Good (joint clearance sensitive)	Very Good	Good	Good
Peel Test Failure	Base Metal	Base Metal	Base Metal	Base Metal

* See Appendix A for definitions.

Table 4

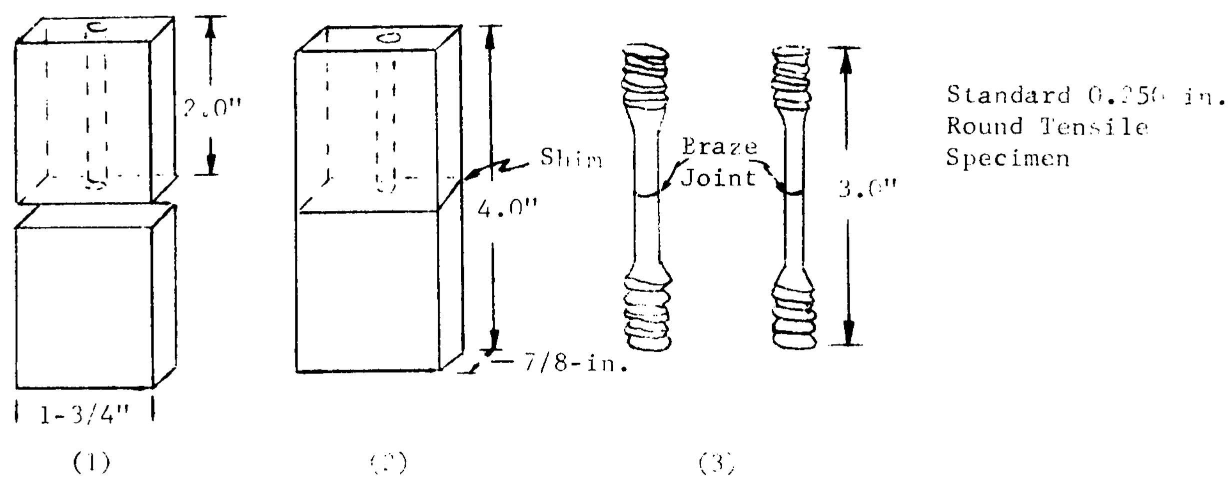
AWS LAP SHEAR SPECIMEN



1. Machine blanks, vapor degrease, grit-blast mating surfaces, hydrogen bright anneal, shim edge of specimen, tack weld edge of specimen, apply braze alloy, and furnace braze.

2. Machine specimen and test.

TENSILE SPECIMEN



(1) Machine blocks, vapor degrease, grit-blast mating surfaces, hydrogen bright anneal.
(2) Shim edge of block, tack weld at corners, apply braze alloy into feed hole, and furnace braze.
(3) Machine specimens and test.

Figure 1

Lap Shear and Tensile Test Specimens

The tests were conducted at room temperature and at -423°F. Each specimen was pulled on a Tinius-Olsen tensile machine with a cross-head travel rate of 0.1-in.-per-minute until failure occurred. Ultimate strengths were calculated and are shown in Tables 5 and 6.

D. EVALUATION AND QUALIFICATION TESTS

The following nine basic tests were performed to qualify the systems.

1. Test 1 - Determination of Chemical Compositions

The tests were conducted on as-received alloys using the spectrographic and wet chemistry techniques to cross-reference the results. All alloys met the established chemical compositions.

2. Test 2 - Determination of Liquidus and Solidus Temperatures

The alloys were checked using the cooling curve technique and visual reference test, whereby the alloy is placed in a vacuum furnace with thermocouples located in close proximity to the alloys. The thermocouples are observed during the heating and cooling cycle. Near-identical results were obtained ($\pm$ 10°F).

3. Test 3 - Braze Temperature Determination

Several tests were conducted for each alloy system to obtain proper flow characteristics. Generally, a temperature of approximately 50°F to 70°F above the rated liquidus produced good flow characteristics.

4. Test 4 - Determination of Diffusion and Erosion Characteristics

Microstructural examination was made to determine the rate of diffusion and erosion. No erosion could be detected when using the braze temperatures considered optimum; however, AGC-202A, AGC-204A, and AGC-206A diffused between 0.001-in. to 0.002-in. A direct relationship exists between silicon content and diffusion (see Tables 3 and 4).

5. Test 5 - Brazement Hardness

Micro hardness surveys were made on the resulting brazements. A range in hardness from R_B 58 to R_B 89 was obtained. Further investigation revealed that the alloy systems which exhibited 0.003-in. diffusion had a hardness range in excess of R_C 40.

6. Test 6 - Wet and Flow Characteristics

The wet and flow characteristics were determined by the ability or inability of the braze filler metal to wet and flow up vertical test specimens (two 6-in. long 0.020-in. tubes, Type 347, tack welded at the

LAP SHEAR TEST RESULTS

SS
Ultimate Shear Strength, K.S.I.

(Base Metal Type 347 SS-0.002 in. Joint Clearance)

"2T"

Braze Alloy	Room Temperature	SS -423°F	Position-Relative Strength Room Temperature	-423°F
AGC 200	44.4*	73.6	4	2
AGC 201	47.6*	72.3	1	3
AGC 202A	38.0	57.4	6	9
AGC 202B	34.0	57.6	10	8
AGC 204A	26.9	49.3	12	11
AGC 204B	34.4	59.4	9	6
AGC 206A	29.1	40.7	11	12
AGC 206B	36.6	60.6	7	5
Anaconda 651	45.2	61.0	2	4
Anaconda 656	44.3	51.9	5	10
OFHC Copper	35.9	58.3	8	7
Wesgo-Nicoro	45.1*	78.4	3	1

* Specimens failed in base metal.
AGC 200 -- All three specimens failed in base metal.
AGC 201 -- All three specimens failed in base metal.
Nicoro --- One specimen failed in base metal.

Table 5

TENSILE TEST RESULTS

SS

Ultimate Tensile Strength K.S.I.

(Base Metal Type 347 SS-0.003 in. Joint Clearance)

Braze Alloy	Room Temperature	$-423^{o}F$	Position-Relative Strength Room Temperature	Position-Relative Strength $-423^{o}F$
AGC 200	81.5	128.9	2	2
AGC 201	80.8	117.0	3	3
AGC 202A	78.1	78.3	4	8
AGC 202B	65.7	90.6	7	6
AGC 204A	41.9	30.8*	10	11
AGC 204B	54.1	71.7	9	9
AGC 206A	37.6	24.0*	12	12
AGC 206B	41.6	87.2	11	7
Anaconda 651	78.0	95.6	5	5
Anaconda 656	74.7	61.5	6	10
OFHC Copper	56.8	98.3	8	4
Wesgo Nicoro	83.4	166.2	1	1

* Incomplete braze coverage.

Table 6

ends) with a pre-set joint clearance of 0.003-in. using standard brazing temperature and pressure ranging from 0.5 microns to 5.0 microns. The specimens were then visually rated to determine the extent of wetting and flow.

7. Test 7 - Peel Test

The degree of bond strength was determined using the specimens described above by peeling the tube specimen in opposing directions and examining the mode of failure. Failure would occur in either the brazement or the parent metal.

8. Test 8 - Mechanical Properties

Standard A.W.S. lap shear specimens were prepared along with tensile specimens to determine lap shear and tensile strength for each alloy system at room temperature and -423^{o}F.

9. Test 9 - Burst Test

Burst testing of AISI stainless steel brazed tubular specimens was also performed. Three-inch lengths of AISI stainless steel tubing with a 0.020-in. wall were furnace-brazed to a platform of the same material (0.125-in. thick) to perform pressure burst tests. This test was made to determine if thin-walled stainless steel tubing would be embrittled by the braze filler alloys. These specimens are shown in Figures 2 and 3.

The tube ends were fitted with A-N fittings and hydrostatically pressurized until failure occurred. All specimens failed at approximately 5000 psig at the mid-point of the tube.

E. BRAZE JOINT PROPERTIES

The lap shear and tensile properties of the alloys investigated are shown in Tables 5 and 6, respectively. Also included are Nicoro and OFHC copper as reference data.

The alloys containing small percentages of silicon were generally weaker; this is attributed to the formation of a hard iron-silicide phase in the diffusion zone. Test results indicate that the AGC-200, AGC-201, and the Anaconda 651 (low silicon) have closely related ultimate shear strengths and are comparable with Nicoro, the prime commercial candidate alloy. The same relationship of strength is apparent for the ultimate tensile strength, with the exception of Anaconda 651 which had a lower ultimate tensile strength than OFHC copper at -423^{o}F.

F. METALLOGRAPHIC EXAMINATION OF BRAZE JOINTS

The photomicrographs illustrated in Figures 4 through 14 are typical tube joints brazed with the different braze filler materials investigated. The base metal in all tests is Type AISI 347 hydrogen-annealed stainless steel tubing.

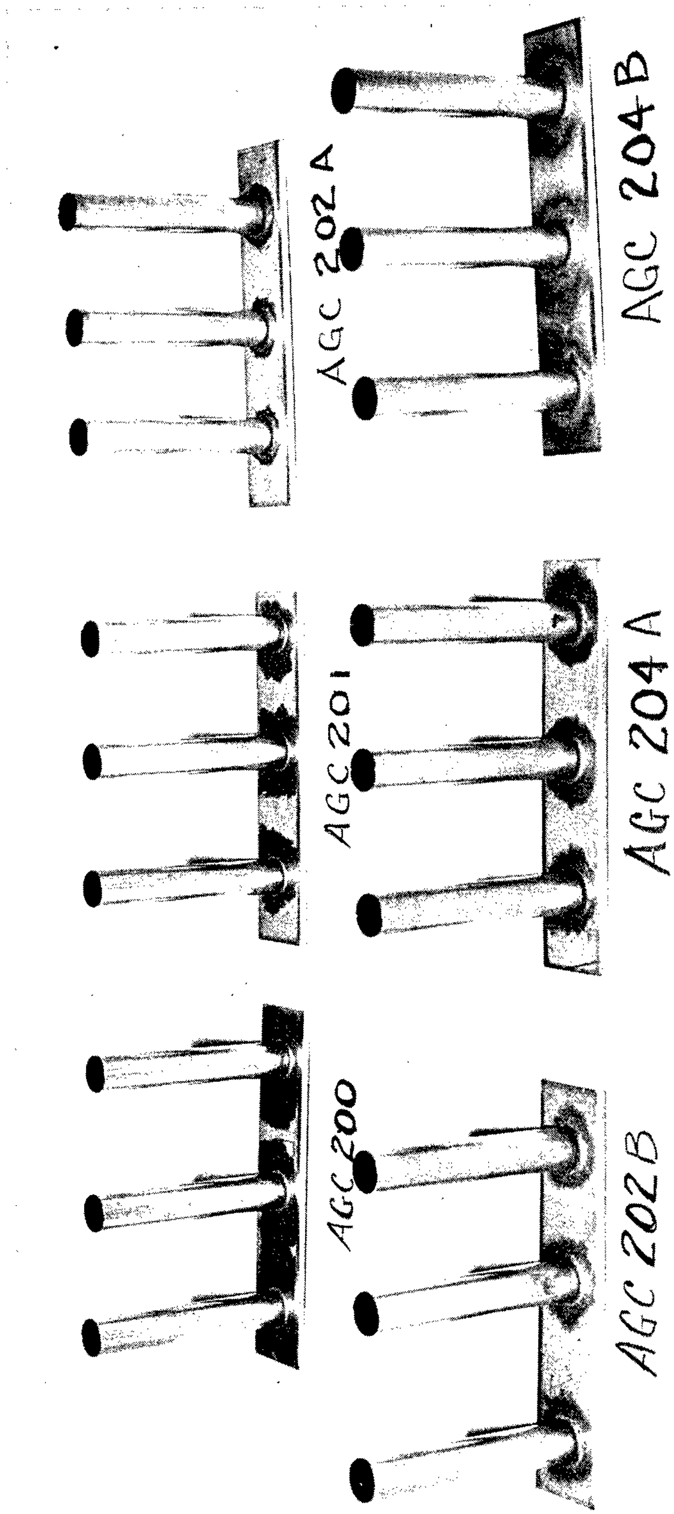


Figure 2
Brazed Specimens for
Pressure Testing

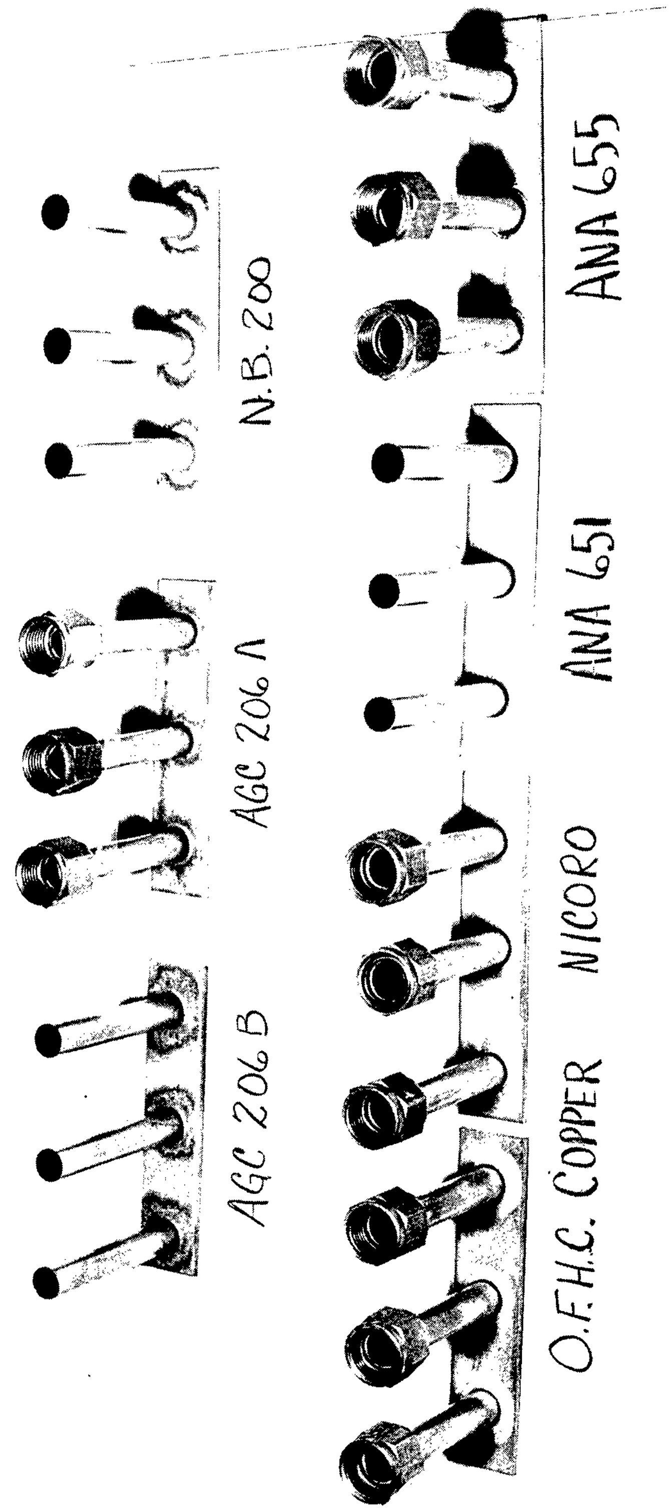


Figure 3
Brazed Specimens for
Pressure Testing

The following observations were made during the course of evaluating the alloy systems.

1. AGC-200 - A Solid-Solution Alloy

No phase change or secondary phases could be detected. Minimal diffusion into the base metal was observed. Braze deposit microhardness average (based upon several surveys) was R_B 58 (see Figure 4).

2. AGC-201 - A Solid-Solution Alloy

No phase change or secondary phases could be detected and there was minimal diffusion into the base metal. Braze deposit microhardness average was R_B 60 (see Figure 5).

3. AGC-202A - A Peritectic and Solid-Solution Alloy

Formation of a secondary phase was noted together with a hard diffusion boundary. The diffusion boundary is attributed to the formation of iron-silicides. Average hardness of brazement was R_B 60; average hardness of diffusion zone was R_C 38 (see Figure 6).

4. AGC-202B - A Multi-Phase Structure, Solid-Solution and Peritectic Alloy

There is minimal diffusion into the base metal. The lower silicon content in this alloy limited the formation of the iron-silicide noted for AGC-202A. Average microhardness of the brazement was R_B 94 (see Figure 7).

5. AGC-204A - A Peritectic and Solid-Solution Alloy

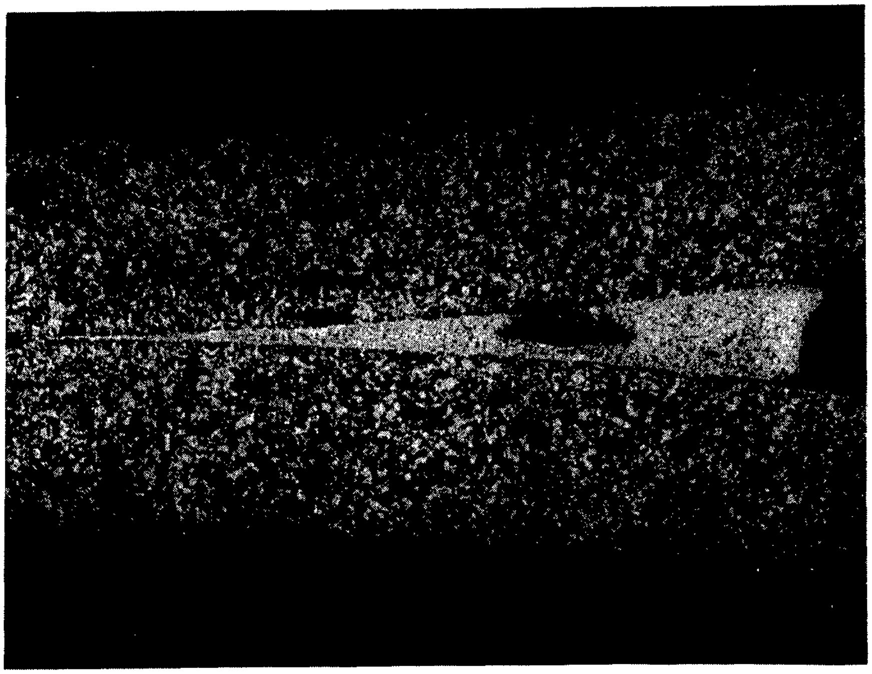
Formation of a secondary phase and a hard diffusion boundary was noted. The diffusion boundary is attributed to the formation of iron-silicide. Average microhardness of the brazement was R_B 84; average hardness of diffusion zone was R_C 52 (see Figure 8).

6. AGC-204B - A Multi-Phase Structure, Solid-Solution and Peritectic Alloy

There is minimal diffusion into the base metal. The lower silicon content in this alloy limited the formation of iron-silicide experienced with alloys AGC-202A and AGC-204A (see Figure 9).

7. AGC-206A - A Multi-Phase Structure, Solid-Solution and Peritectic Alloy

The presence of an intermetallic compound was not observed. The silicon preferentially combined with the palladium and nickel resulting in a network of void areas. Consequently, AGC-206A resulted in the poorest joint strength (see Figure 10).



Hardness

R_B 88

R_B 86

R_B 84

Off of R_B Scale

Magnification: 100X

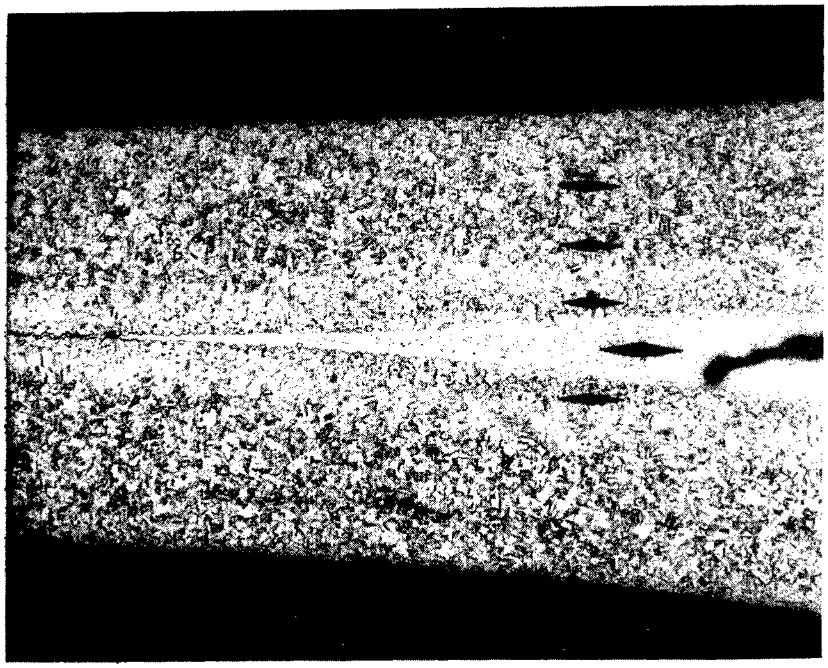
AGC 200 alloy, vacuum furnace brazed at 1970°F/15 min.

Etchant: Picral - HCl

AGC 200	
Cu	Bal.
Au	15.0
Pd	4.5
Ni	3.0

Figure 4

PHOTOMICROGRAPH, AGC-200



Hardness
R_B 92
R_B 91
R_B 91
R_B 62
R_B 91

Magnification: 100X

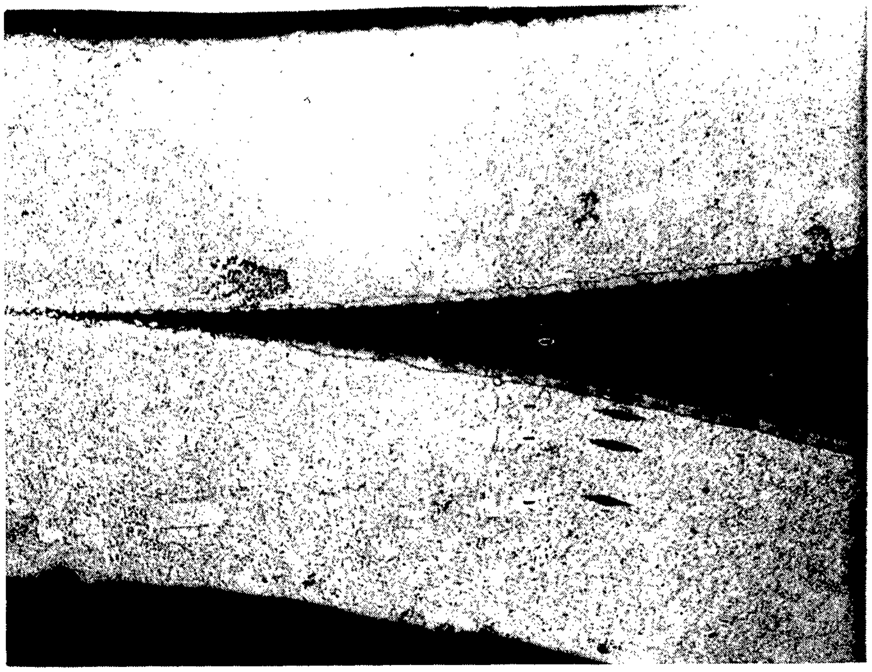
AGC 201 alloy, vacuum furnace brazed at 1970°F/15 min.

Etchant: Picral - HCl

AGC 201	
Cu	Bal
Au	15.0
Pd	5.0
Co	5.0

Figure 5

PHOTOMICROGRAPH, AGC-201



Hardness

R_B 69
R_C 38
R_B 97
R_B 97

R_B 97

Magnification: 100X

AGC 202A alloy, vacuum furnace brazed at 1900°F/15 min.

Etchant: Picral - HCl

<u>AGC 202A</u>

Cu bal
Si 3.5-4.0
Ni 0.5-1.5
Pd 0.5-1.0

Figure 6

PHOTOMICROGRAPH, AGC-202A

Hardness

R_B 98
R_B 98
R_B 99
R_B 99

R_B 97

Magnification: 120X

AGC 202B alloy, vacuum furnace brazed at 1950°F/15 min.

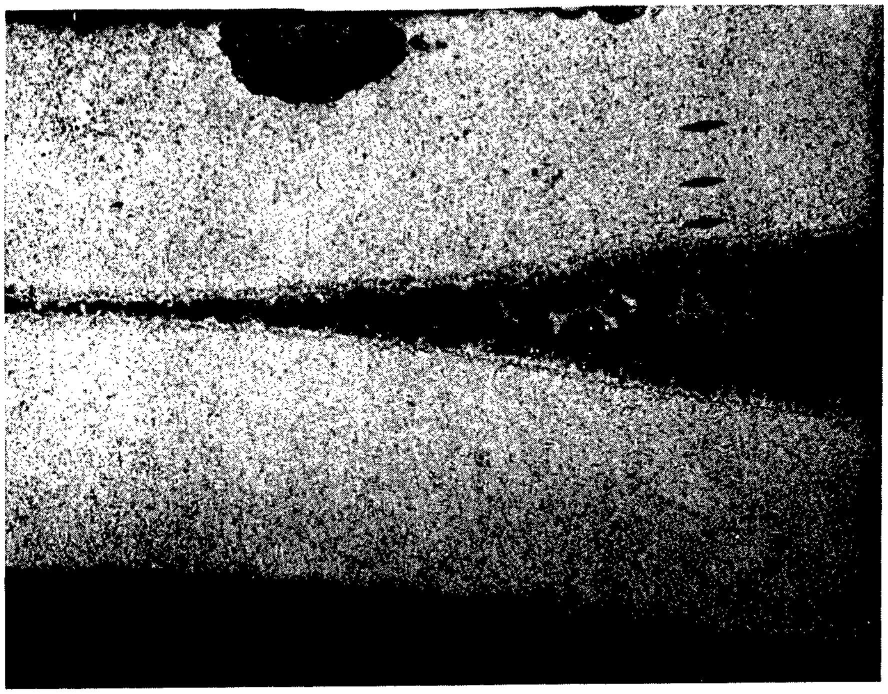
AGC 202B

Etchant: Picral - HCl

Cu bal
Si 1.5-2.0
Pd 0.5-1.5
Ni 0.5-1.0

Figure 7

PHOTOMICROGRAPH, AGC-202B



Hardness

R_B 92

R_B 97

R_B 98
R_C 53 R_C 52

R_B 87

Magnification: 120X

AGC 204A alloy, vacuum furnace brazed at 1900°F/15 min.

AGC 204A

Cu bal
Si 3.5-4.0
Pd 5.0-6.0
Ni 3.3-4.0

Etchant: Picral - HCl

Figure 8

PHOTOMICROGRAPH, AGC-204A

Hardness

R_B 97

R_B 98
R_B 98
R_B 98

R_B 92

Magnification: 120X

AGC 204B alloy, vacuum furnace brazed at 1970°F/15 min.

AGC 204B

Cu bal
Si 1.5-2.0
Pd 5.0-6.0
Ni 3.3-4.0

Etchant: Picral - HCl

Figure 9

PHOTOMICROGRAPH, AGC-204B

Hardness

R_B 95

R_B 95
R_B 91

R_B 95

R_B 92

Magnification: 120X

AGC 206A alloy, vacuum furnace brazed at 1900°F/15 min.

AGC 206A

Cu bal
Si 3.5-4.0
Pd 9.0-10.0
Ni 6.0-6.75

Etchant: Picral - HCl

Figure 10

PHOTOMICROGRAPH, AGC-206A

8. AGC-206B - A Multi-Phase Structure, Solid-Solution and Peritectic Alloy

There was evidence of a minor amount of diffusion. The diffusion boundary did show the presence of a hard intermetallic compound which indicated an average microhardness equivalent to R_C 42 (see Figure 11).

9. Anaconda 651 (1015) - A Solid-Solution Alloy

No secondary phases could be detected. A hard diffusion boundary was present and is attributed to the formation of iron-silicide. Average hardness of the brazement was R_B 52; average hardness of the diffusion zone was R_C 30 (see Figure 12).

10. Anaconda 656 (1010) - A Multi-Phase Structure, Solid-Solution and Peritectic Alloy

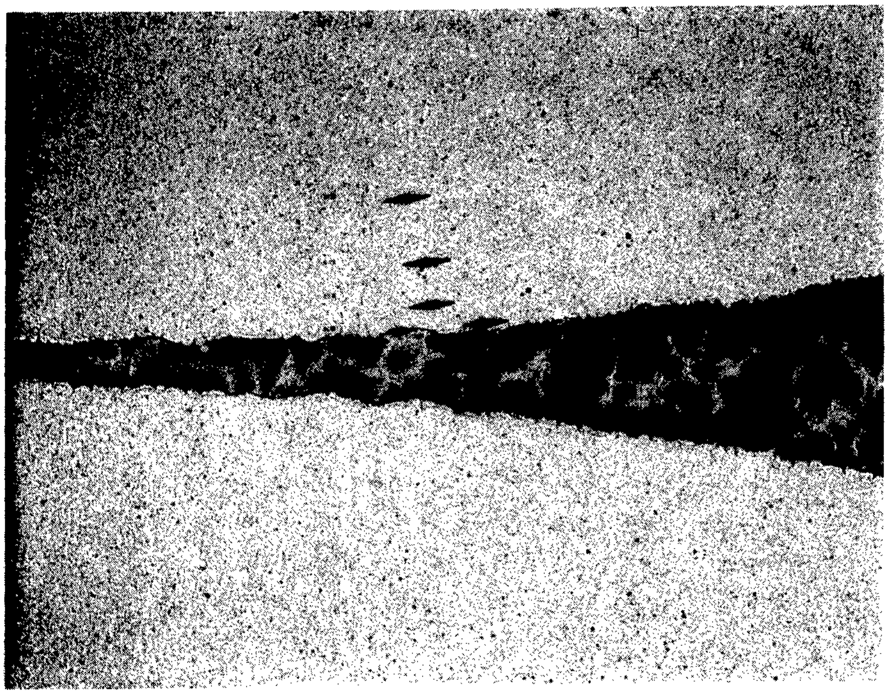
A sharp line of diffusion is present and is clearly shown in the photomicrograph. The diffusion zone gave an average hardness of R_C 33 (see Figure 13).

11. Wesgo Nicoro - A Solid-Solution Alloy

Average hardness was R_B 68. A minimal amount of diffusion was noted (see Figure 14).

IV. CONCLUSIONS

Of the eight alloy systems developed in this program, two, AGC-200 and AGC-201, compare most favorably with the prime commercial candidate, Nicoro. A cost savings of approximately 50% could be realized if either of these alloys were used in place of Nicoro. The net savings for each M-1 Thrust Chamber is estimated to be $7,000.00. The commercial product Anaconda 651 also appears promising; however, additional research would have to be conducted to purify the analysis and to make further study of the union of silicon, iron, and nickel. All alloy systems, both commercial and Aerojet-General developed, with the exception of AGC-206A exhibited good braze characteristics and good strength levels. AGC-200 and AGC-201 has outstanding wet and flow characteristics and is insensitive to joint clearance variations. Both AGC-200 and AGC-201 are solid-solution type alloys free from any brittle intermetallic compounds such as is observed in the silicon-bearing alloys. The commercial product Nicoro is also a solid-solution alloy and as the results indicate in this report, the joint strength was the highest for these three alloys for both lap shear and tensile strength at room temperature and -423°F.



Hardness

R_B 97

R_B 96

R_B 97

R_C 44 R_B 98

R_B 92

Magnification: 120X

AGC 206B, vacuum furnace brazed at 1975°F/15 min.

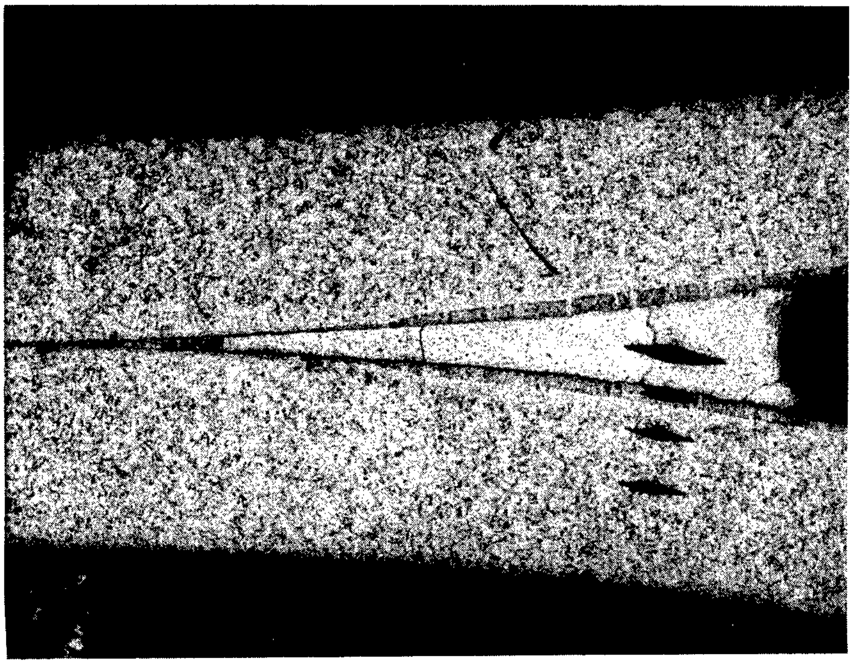
AGC 206B

Cu bal
Si 1.5-2.0
Pd 9.0-10.0
Ni 6.0-6.75

Etchant: Picral - HCl

Figure 11

PHOTOMICROGRAPH, AGC-206B



Hardness

R_B 49

R_C 28

R_B 90

R_B 91

Magnification: 100X

Anaconda 651 alloy, vacuum furnace brazed at 1960°F/15 min.

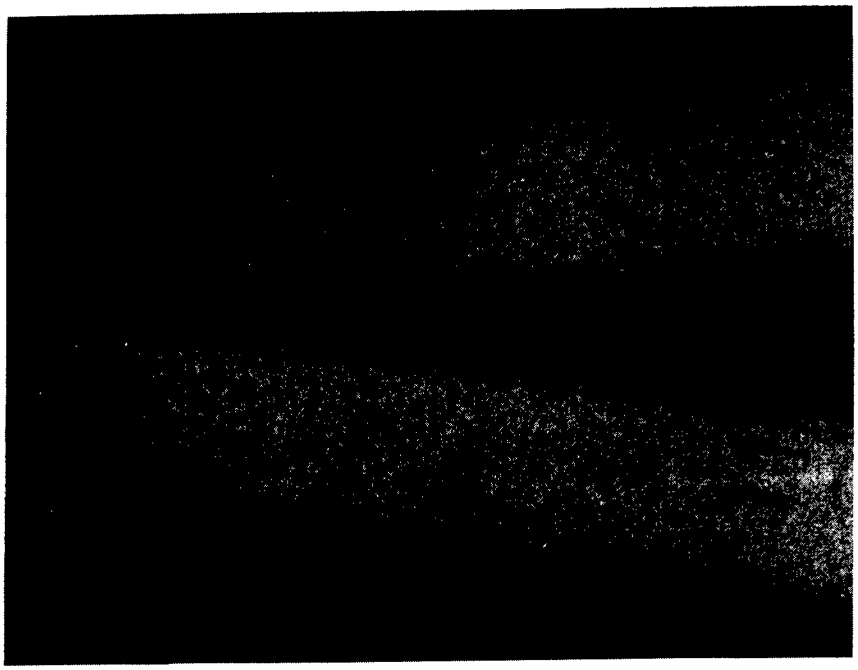
Anaconda 651

Cu Bal
Si 1.5
Mn .25

Etchant: Picral - HCl

Figure 12

PHOTOMICROGRAPH, ANACONDA 651



Hardness

R_B 47
R_C 30
R_B 88
R_B 88

Magnification: 100X

Anaconda 656 alloy, vacuum furnace brazed at 1900°F/10 min.

Anaconda 656

Etchant: Picral - HCl

Cu Bal
Si 3.1
Mn 1.1

Figure 13

PHOTOMICROGRAPH, ANACONDA 656

Hardness

R_B 98

R_B 68

Magnification: 120X

Nicoro alloy, vacuum furnace brazed at 1925°F/15 min.

Nicoro

Cu 62.0
Ni 3.0
Au 35.0

Etchant: Orthophosphoric Acid

Figure 14

PHOTOMICROGRAPH, NICORO

V. RECOMMENDATIONS

The braze alloys AGC-200, AGC-201, Anaconda 651, and Nicoro should be evaluated further with respect to their behavior on specimens made from full-length thrust chamber tubes. Braze filler metal volume and distribution control, joint-making capacity, and possible erosion effects, when used for making long joints involving considerable gravitational flow, need to be established to verify suitability in this critical application.

APPENDIX A - DEFINITIONS

1.	Liquidus	The temperature at which complete melting has occurred.
2.	Wet and Flow	The ability or the inability of the braze material to flow and wet on a vertical test specimen (6-in. long tubing) with a pre-set joint clearance of 0.003-in. at the standard brazing temperature and pressures ranging from 0.5 microns to 5.0 microns (visually rated).
3.	Diffusion	The depth of braze alloy penetration into the base metal. May be in the form of intergranular diffusion, mass diffusion, or solutioning effect.
4.	Erosion	The depth of, or the extent of surface dissolution of the base material being brazed.
5.	Microhardness	Hardness survey of micro-constituents.
6.	Peel Tests	The mode of failure experienced when brazed tube specimens are peeled in opposite directions. Failure will occur in the brazement or the parent metal.
7.	Lap Shear	Lap shear specimens tested for mode of failure and shear strength of brazement. (Standard A.W.S. Lap Shear Specimen.)
8.	Tensile	Tensile testing to determine the tensile strength of the brazement.

NASA-Langley, 1966 E-3376

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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